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Spatiotemporal Analysis of Prior Appropriations Water Calls

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[1] A spatiotemporal model is developed to examine prior appropriations–based water curtailment in Idaho's Snake River Plain Aquifer. Using a 100 year horizon, prior appropriations–based curtailment supplemented with optimized water use reductions is shown to produce a spatial distribution of water use reductions that differs from that produced by regulatory curtailment based strictly on initial water right assignments. Discounted profits over 100 years of crop production are up to 7% higher when allocation is optimized. Total pumping over 100 years is 0.3%, 3%, and 40% higher under 1, 10, and 100 year prior appropriations–based regulatory curtailment, respectively.

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1. Introduction

[2] Groundwater levels in many aquifers have been declining as a consequence of factors such as droughts, climate change, increased groundwater pumping, adoption of more efficient sprinkler irrigation technology that reduces incidental recharge, and the expansion of irrigated agriculture [*Cosgrove et al.*, 2008]. Declining water availability, often coupled with increasing water demand, can increase the number of costly water conflicts [*Slaughter and Wiener*, 2007; *Baker and Willis*, 2006; *Jaeger*, 2004; *Boehlert and Jaeger*, 2010]. Rapid population growth (U.S. Census, Population census: Resident population data, http://2010.census.gov/2010census/data/apportionment-pop-text.php, accessed 10 February 2011) and projected climatic changes [*Bates et al.*, 2008] are likely to intensify water disputes.

[3] Prior appropriations (PA) doctrine relies on the tenet of "first in time, first in right" and operates under a continuum of relative priority of water rights held by water users on the basis of seniority. During periods of water shortage, PA doctrine allows relatively senior water rights holders to place water calls to meet their water rights, if they believe that their water rights are impaired by water use of junior right holders. If a water call is granted, the administrative authority issues a curtailment order that forces junior rights holders to reduce their water use. It is important to emphasize that PA doctrine is the predominant system for establishing initial water endowments within the western United States and provides a mechanism for water allocation during shortages. While PA does not itself preclude transfer of water rights, substantial transaction costs and ambiguities pertaining to the hydrologic externalities of such transfers can preclude water right transfers from taking place [*Young*, 1986]. Supplementing PA doctrine with well-designed temporary reallocation policies that account for hydrologic externalities and reduce transaction costs could improve economic efficiency, in the sense of potential Pareto improvement, when a water call is placed. For example, if appropriate temporary water reallocation policies are in place, then junior water users subject to curtailment can negotiate with senior water users and pay them to cut back on their water use enough to satisfy the call made by senior water users. This would be consistent with Coasian bargaining, which results in the optimal allocation of resources through mutual bargaining, assuming no transaction costs, irrespective of the initial allocation of property rights [*Coase*, 1960]. Following the logic of *Gisser* [1983], the objective in this paper is to examine the potential magnitude of welfare gains measured by the change in the discounted present value of combined regional profits from agricultural production if costless water reallocation policies are in place. Transaction costs associated with implementing such policies are not addressed in this paper. Nevertheless, it is important to investigate the extent to which water reallocation policies might produce potential Pareto improvements even before transaction costs are explicitly considered.

[4] Prior appropriations–based administrative curtailment that is not supplemented with water right reallocation as a component of overall response to water shortage may produce economically efficient outcomes in some cases but not in others. The spatial distribution of water right seniority coincide with the spatial distribution of agricultural soil productivity if the most productive land was developed first and was granted senior water rights. In such a situation, curtailment according to seniority of water rights approximates the economically efficient pattern of curtailment in terms of soil productivity. However, land development is often constrained as much by access to infrastructure as by soil productivity. Therefore, relatively more productive land can in some cases have relatively junior water rights. For example, among surface water rights, lands nearest watercourses often have senior priorities regardless of soil productivity. In eastern Idaho, these gravelly alluvial soils are often less productive than distant wind-deposited soils. Among groundwater rights, lands nearest adequate

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electrical transmission lines can have senior priorities regardless of soil productivity. Further, PA-based management, not supplemented with the opportunity for temporary water reallocation, does not account for linkages between the economic and hydrologic attributes of the water basin. When water right seniority does not coincide with soil productivity, and/or in cases where soil productivity and hydrologic connectivity are not spatially homogeneous such PA-based curtailment may produce suboptimal outcomes. Regional hydrologic and economic attributes play significant roles in the selection of site-specific conjunctive management strategies that result in economically efficient allocation of scarce water resources across space and time in the sense of potential Pareto optimality where ground and surface water are hydraulically connected.

[5] In this paper we use the combined present value of regional profits from agricultural crop production as the measure of economic efficiency. We provide a hydroeconomic theoretical framework and a corresponding empirical model that couples economic and hydrologic considerations to determine economically optimal, spatially explicit, groundwater management policies during water shortages. A simulation-based empirical application of the framework is presented for the Eastern Snake River Plain Aquifer (ESRPA) in southern Idaho (Figure 1), currently experiencing significant water rights disputes. The economic implications of water management decisions in this region are tremendous, involving two million irrigated agricultural acres, numerous hydropower facilities, municipalities, and the largest producers of trout in the United States. Decreasing groundwater levels led to the formation of the Comprehensive Aquifer Management Plan [*Idaho Department of Water Resources* (*IDWR*), 2009], which was passed in 2009 to remedy aquifer depletion through conjunctive management.

[6] A profit maximization model for the region's agricultural industry is integrated with spatiotemporal hydrologic response functions for each geographically explicit zone of

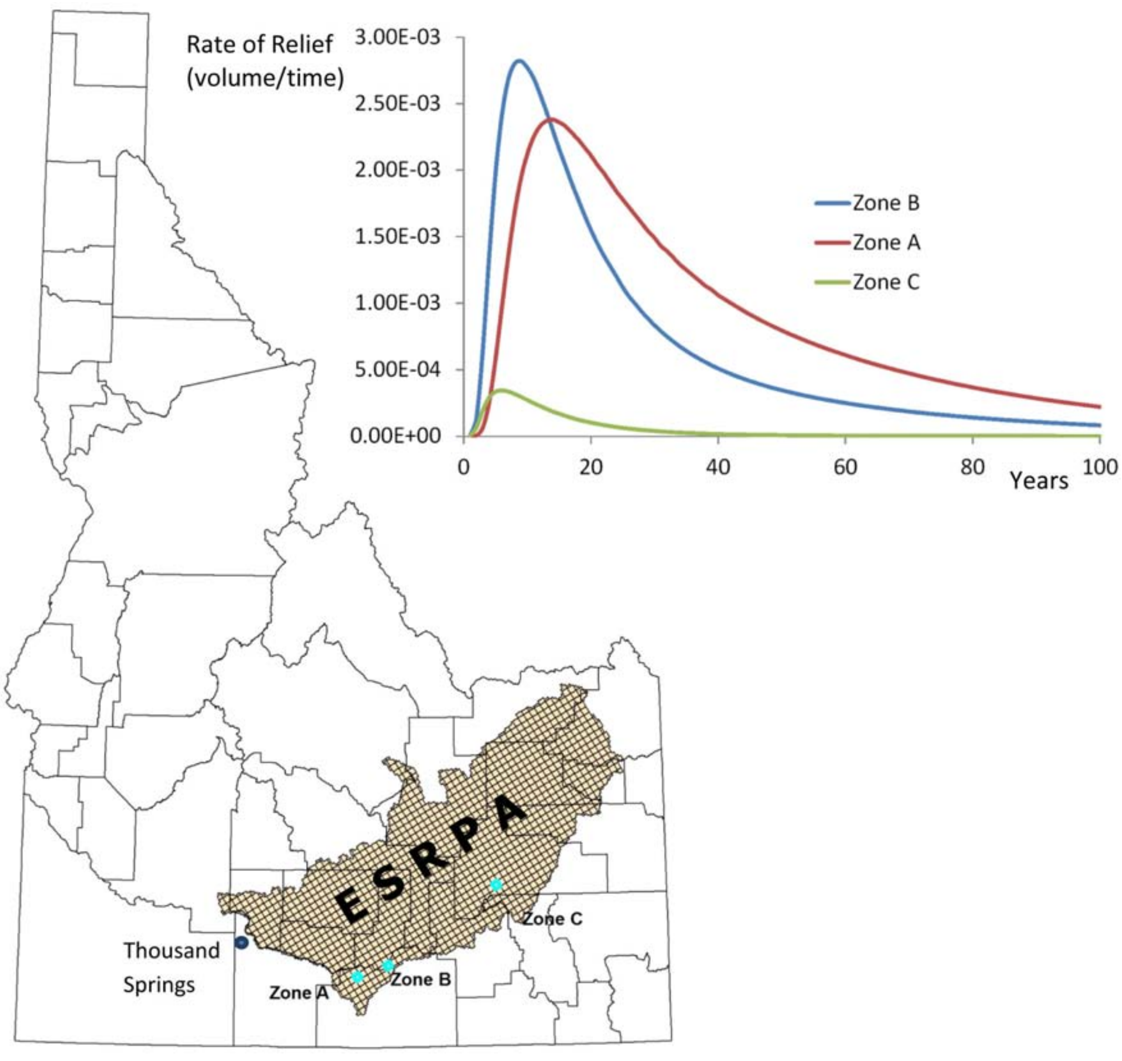

Figure 1. Eastern Snake River Plain Aquifer (ESRPA) in Idaho and the dynamic response functions that express the effects of 1 acre-foot reduction in consumptive use in three different zones (A, B, and C) on discharge at Thousand Springs. Integration of a response function from $t = 0$ to $t = t'$ provides total volume of additional relief at the target area (Thousand Springs) produced by reducing consumptive use of groundwater in that zone by 1 AF.

the Eastern Snake River Plain (ESRP). The empirical model is used to compare the relative economic efficiency of prior appropriations–based curtailment [*Contor et al.*, 2006] under the assumptions of with (PAR) and without (PA) temporary water reallocation. Under the PAR scenario, water use implied by PA can be reallocated on the basis of maximizing the combined regional discounted profits under the assumption of zero transaction costs. The PAR mechanism is constrained to meet the call made by senior water users and deliver an amount of water no less than the amount delivered under PA to the target area (the reach where senior water users issue a call demanding that junior water users be managed in accordance with prior appropriations doctrine). The framework has a number of novel attributes, including (1) incorporation of spatial as well as temporal considerations of the hydrologic system in concert with economic decisions, (2) incorporation of soil productivity as well as hydrologic connectivity in designing a management strategy, (3) quantification of potential benefits of enhancing the PA-based water allocation with a policy that would facilitate optimized water use (the estimated benefits can be used as an upper bound of potential transaction costs for feasibility of implementing such policy), and (4) illustration of empirical results using maps. This is useful for illustrating the consequences of alternative ways of resolving water conflicts to individual stakeholders and policy makers.

2. Analytical Framework

[7] Prior research has shown the effects of distance, and associated conveyance losses during water delivery, on the spatial allocation of irrigation water [*Chakravorty and Roumasset*, 1991]. We add to this work by examining the problem of conjunctive administration of groundwater given its effect on surface water rights, incorporating temporal and spatial dimensions. Similar to previous studies [*Vaux and Howitt*, 1984; *McCarl and Parandvash*, 1988; *Michelson and Young*, 1993; *Ward and Lynch*, 1997, *Tanaka et al.*, 2006; *Booker et al.*, 2005] our project focuses on water distribution between multiple irrigation zones (an individual zone comprises all groundwater-irrigated lands within a single block of a regular rectangular grid).

[8] Assuming a planning horizon *T*, producers maximize total profits from agricultural crop production with *I* irrigation zones as $\sum_{z}^{I}\sum_{t=0}^{T} e^{-r\tau}R_{zt}(w_{z\tau})$, where z are individual irrigation zones, r is the discount rate, and $R_{z\tau}(w_{z\tau})$ is profit in irrigation zone z in period τ as a function of pumped groundwater, $w_{z\tau}$. Faced with a water shortage senior surface water rights holders can exercise their right to make a water call to receive B_t amount of relief (i.e., additional water) in time period t at a specific location (henceforth referred to as the target area), consistent with their rights. Thus, B_t can be interpreted as the amount of relief that would be produced by the administrative curtailment to which the administrative agency determines that the senior user is entitled. Let $\bar{w}_z$ represent the maximum amount of groundwater pumped in each irrigation zone under no water shortage. Another way to interpret $\bar{w}_z$ is the unconstrained pumping volume bounded only by the individual groundwater rights.

[9] Under the PAR scenario, the requirement that senior appropriators issuing a water call in the target area receive at least B_t amount of additional water can be expressed as $\sum_{z}^{Z}\left[\sum_{\tau=0}^{t}(\bar{w}_z - w_{z,\tau})\Psi_{t-\tau}(d_z)\right] \geq B_t,\ \forall t,$ where $(\bar{w}_z - w_{z,\tau})$ is a decrease in groundwater use (pumping) in irrigation zone z in period τ, and B_t is the relief that would have been afforded in period t by the prior appropriation–based curtailment. t denotes the period in which the relief at the target area is realized, and τ represents the period when pumping was reduced in a given zone. $\Psi_{t-\tau}(d_z)$ is the hydrologic response function showing the amount of relief at the target area in period t after a 1 acre-foot (ac ft, 1 ac ft = 1234 m^3) decrease in consumptive use in zone z in period τ, or $t-\tau$ periods ago. Therefore, $\sum_{z}^{Z}\left[\sum_{\tau=0}^{t}(\bar{w}_z - w_{z,\tau})\Psi_{t-\tau}(d_z)\right]$ measures the cumulative amount of relief at the target area in period t from reductions in pumping in all zones during preceding periods. The response function is specified as a function of transient hydraulic distance (d_z) from zone z to the target area (G. S. Johnson et al., Snake River Basin surface water—ground water interaction, 1998, available at http://www.if.uidaho.edu/_johnson/ifiwrri/sr3/home.html). The greater the hydraulic distance between the target area and an irrigation zone, z, the smaller the proportion of decrease in consumptively used groundwater that propagates from irrigation zone z to the target area. Taken in its entirety, the above constraint requires the PAR scenario to supply groundwater contributions to the target area (i.e., river gains or spring flow at the reach of interest) from all irrigation zones that is no less than the relief B_t provided by regulatory curtailment, PA, in each time period. Under the PA solution to the water call, B_t is generated by curtailing enough water users who are junior to the users issuing the call, until the requirements of the call are met.

[10] The Lagrangian for the social planner's optimization under the PAR scenario is

$$\max_{w_{z\tau}} : L = \sum_{z}^{Z}\sum_{\tau=0}^{T} e^{-r\tau}R_{z\tau}(w_{z\tau}) + \sum_{t=0}^{T}\left\{\lambda_t \sum_{z}^{Z}\left[\sum_{\tau=0}^{t}(\bar{w}_z - w_{z,\tau})\Psi_{t-\tau}(d_z)\right] - B_t\right\} \tag{1}$$

The first-order condition is as follows:

$$e^{-rt}R'_{z\tau}(w_{z\tau}) - \sum_{t=\tau}^{T}\lambda_t\Psi_{t-\tau}(d_z) = 0 \qquad \forall z,\tau \tag{2}$$

Applying the implicit function theorem [*Simon and Bloom*, 1994], we get

$$\frac{\partial w_{z\tau}}{\partial d_z} = \frac{\sum_{t=\tau}^{T}\lambda_t\Psi'_{t-\tau}(d_z)}{e^{-r\tau}R'_{z\tau}(w_{z\tau})} \qquad \forall z,\tau \tag{3}$$

[11] Expression (3) is positive when $R''_{z\tau}(w_{z\tau}) < 0$ and $\Psi'_{t-\tau}(d_z) < 0$. $R''_{z\tau}(w_{z\tau}) < 0$ implies that the profit function is concave with respect to water used (pumped). $\Psi'_{t-\tau}(d_z) < 0$ implies that decreasing groundwater pumping by 1 ac ft in irrigation zones distant from senior appropriators issuing the water call, contributes less water to the target area than a 1 ac ft reduction in pumping in an irrigation zone close to the target area. Equation (3) states that it is optimal to increase water use (pumping) as distance (d_z) increases between a given irrigation zone, z, and the target area, all else remaining unchanged. Conversely, the most effective way to fulfill the senior water right holders' water calls would be to decrease water use (pumping) at locations closer to the target area. This is a consequence of the underlying spatial hydrologic relationships which mean that a unit reduction in pumping by irrigators close to the target area will supply more water (greater benefit) to the target area, than will a corresponding unit reduction in pumping by an irrigator located at a greater distance from the target area, all else remaining unchanged.

[12] The optimal spatial distribution of pumping reductions will be affected by the relative characteristics of the individual response function as well as by relative soil productivity. Obviously a small reduction on low-productivity lands near the target is more cost-effective than a large reduction on distant high-productivity lands. The trade-off between small reductions on nearby high-productivity land and larger reductions on distant low-productivity lands is less intuitively explicit. Hydrologic connectivity and soil productivity determine the optimal spatial and temporal solution to senior water right holders' water calls. The PA-based mechanism may inadvertently account for relative soil productivity if water right seniority corresponds to soil productivity (i.e., if the most productive soils were settled first). However, explicit consideration of economic productivity is forbidden at least in Idaho prior appropriation law. Furthermore, hydrologic factors affecting the optimal solution are not considered in the PA-based mechanism. The PAR scenario takes both of these factors into consideration.

3. Eastern Snake River Plain Aquifer, Idaho: Background

[13] The highly transmissive ESRPA underlies 26,000 km^2 of southeastern Idaho, a productive agricultural area dependent on irrigation [*Cosgrove and Johnson*, 2005; *Cosgrove et al.*, 2008]. Irrigated agriculture accounts for more than 90% of water use in the region. The area is also home to trout farms, located in the Thousands Springs area (Figure 1), which depend upon the cold and highly oxygenated waters that spring from the walls of the Snake River Canyon to produce over 70% of U.S. trout supplies (U.S. Trout Farmers Association, About farm raised trout, http://www.ustfa.org/consumers/about.html, accessed 15 November 2010). Some aquaculture producers in this area hold water rights that are senior, relative to some of the groundwater pumping rights. In Idaho, springs are legally classified as surface water.

[14] By about 1905, most of the surface water supply in the Snake River Plain was fully allocated, except for the aforementioned springs. Flood irrigation, which provided significant aquifer recharge, contributed to rising aquifer levels and discharge from natural springs. New water rights from springs were developed in the 1920s through 1970s, including along the Thousand Springs Reach of the Snake River. By the 1960s, surface water rights were fully allocated and groundwater use was developing rapidly [*Cosgrove et al.*, 2008]. Eventually, groundwater pumping and the adoption of sprinkler irrigation technologies reduced aquifer recharge, increased withdrawals, and reduced spring discharges [*Cosgrove et al.*, 2008]. As aquifer water levels and associated spring discharges started to decline, competition for water resources between junior users (predominantly groundwater) and senior users (predominantly surface water) intensified, and sparked interest in the interactions between ground and surface water resources.

[15] In 2005, consistent with the prior appropriations doctrine, senior spring water users filed water delivery calls with the IDWR, claiming that extraction by groundwater pumpers in the ESRPA was causing spring flows to decline in the Snake River Canyon at Thousand Springs [*Wilkins*, 2009]. In response to the water call from senior water users, in March 2009, IDWR issued curtailment notices affecting 865 groundwater rights with priority dates later than 16 January 1972. This notice had the potential to affect irrigated production on 41,000 acres of agricultural land. This curtailment was based on hydrologic calculations of water use reductions by junior water users that would generate enough spring flow to fulfill obligations to senior water right owners at the Thousand Springs Reach of the Snake River. The curtailment order was contested and has not been implemented.

4. Empirical Model

[16] The ESRPA spans 18 counties and in this model is divided into 1370 zones, measuring 5 square kilometers each, including 795 zones that have agricultural production. Each zone is characterized with up to 6 soil types that vary in their productivity (based on Natural Resource Conservation Service (NRCS) Soil Data Mart classifications, http://soildatamart.nrcs.usda.gov, accessed January 2010, hereafter referred to as NRCS, 2010), up to 9 crops, two irrigation technologies (gravity and sprinkler), and two water sources (surface and ground). Each zone in our model is represented by a hydrologic response function obtained from the Eastern Snake River Plain Model (ESRPM 1.1) [*Cosgrove and Johnson*, 2005; *Cosgrove et al.*, 2006]. Each response function shows the rate at which additional groundwater becomes available over time at the Thousand Springs reach as a result of a 1 ac ft reduction in consumptively used groundwater in a given zone. Figure 1 shows example response functions for three different zones. The areas underneath the curves are the total volume of contributions to relief at the target area from a 1 ac ft reduction of consumptive use of groundwater in a given zone. For the most part, zones located further away from the target area provide less relief because a greater proportion of reduced consumptive use is expressed at areas other than the target area (similar to conveyance losses in the work by *Chakravorty and Roumasset* [1991]). However, notice that in Figure 1 the relief from zone B in the earlier years is greater than relief from zone A even though zone A is located closer to the target area. This spatial

hydrologic heterogeneity does not necessarily coincide with the logic that zones located further from the target area will produce less relief at the target area than zones located near the target area, as assumed in section 2. The governing physical relationship is hydraulic distance relative to other connected reaches. Hydraulic distance is a function of the aquifer storage coefficient, aquifer transmissivity and geographic distance [*Theis*, 1941].

[17] The other factor affecting the optimal spatiotemporal distribution of curtailment is the spatial distribution of soil productivity. Soil classifications in the ESRP range from 2 (most productive) to 6 (least productive). Figure 2 shows the spatial distribution of soil productivity in the region. Figure 3 shows the spatial distribution of consumptively used groundwater corresponding to water rights junior to 1973 per zone. Combined, Figures 2 and 3 demonstrate that there is a limited coincidence between the amount of water rights junior to 1973 and the amount of less productive soils across zones.

4.1. Economic Component

[18] Several studies have addressed the economics of conjunctive water management in numerous regions including the Snake River Plain. *Briand et al.* [2008] use positive mathematical programming [*Howitt*, 1995] to study the effects of Snake River flow augmentation on farm profitability. Their model allowed adjustment in land use patterns but not water applications, arguing that because of the lack of substitutes for water in agricultural production farmers will adjust cropping patterns rather than change irrigation application rates. In contrast, our model allows for both crop portfolio and water application rates (deficit irrigation) to be determined endogenously.

[19] Consistent with the objective function in equation (1), the discounted present value of profits from agricultural production across the region is given by

$$\text{Obj} = \sum_{z,c,s,i,ws,\tau} e^{-r\tau}\left[p_{c,z}Y_{z,c,s,i,ws,\tau}(w_{z,c,s,i,ws,\tau})x_{z,c,s,i,ws,\tau} - C_{z,c}x_{z,c,s,i,ws,\tau} - CW_{z,i}w_{z,c,s,i,ws,\tau}x_{z,c,s,i,ws,\tau}\right] \quad (4)$$

where r is the discount rate, $p_{c,z}$ is price of crop c produced in zone z (prices received by producers in different zones are allowed to vary to reflect transportation costs); $Y_{z,c,,s,i,ws,\tau}$ $(w_{z,c,i,ws,\tau})$ is per acre yield of crop c, in zone z, on soil type s, under irrigation technology i and water source, ws (ground or surface), in time period τ, as a

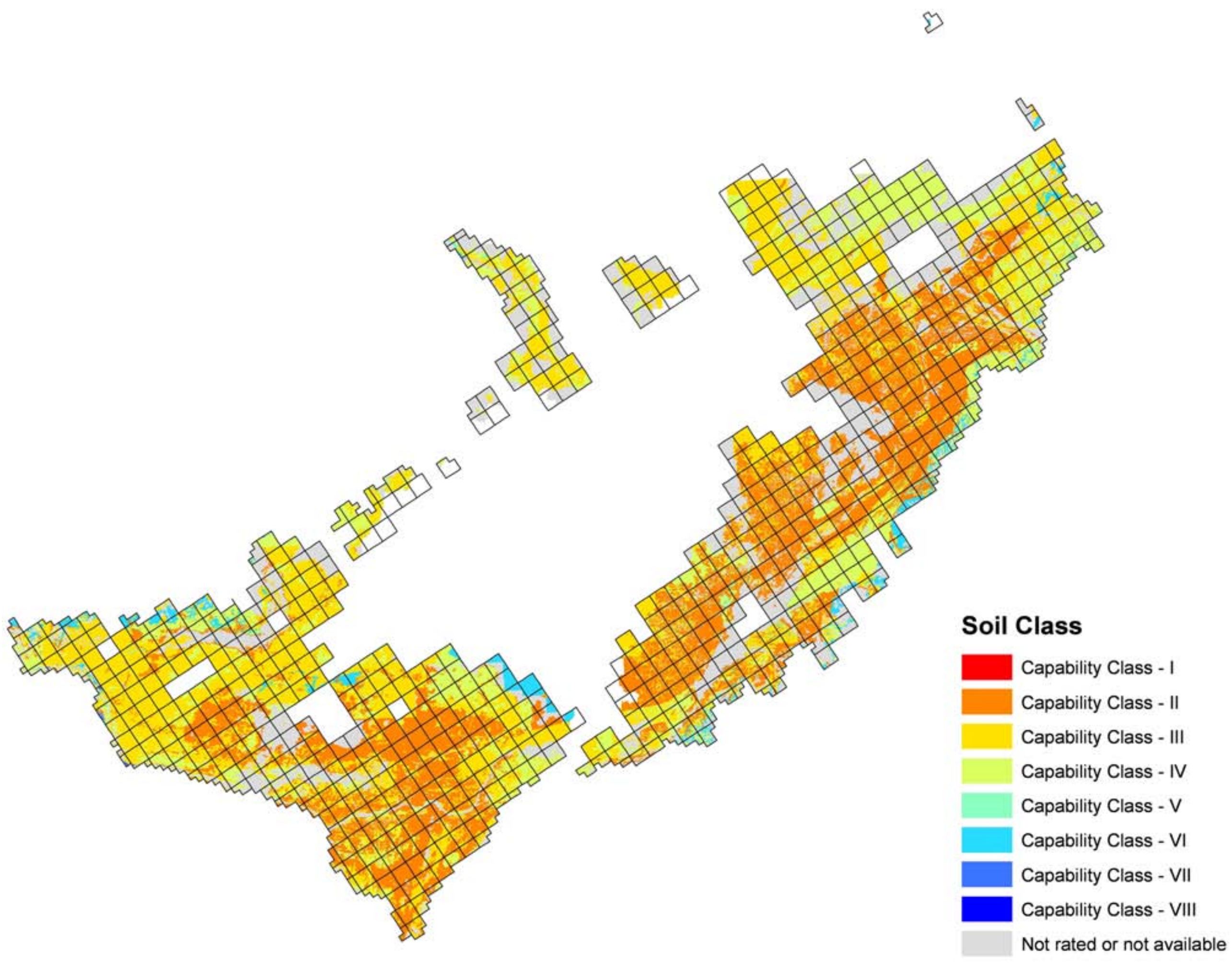

Figure 2. Spatial distribution of soil classes in ESRPA.

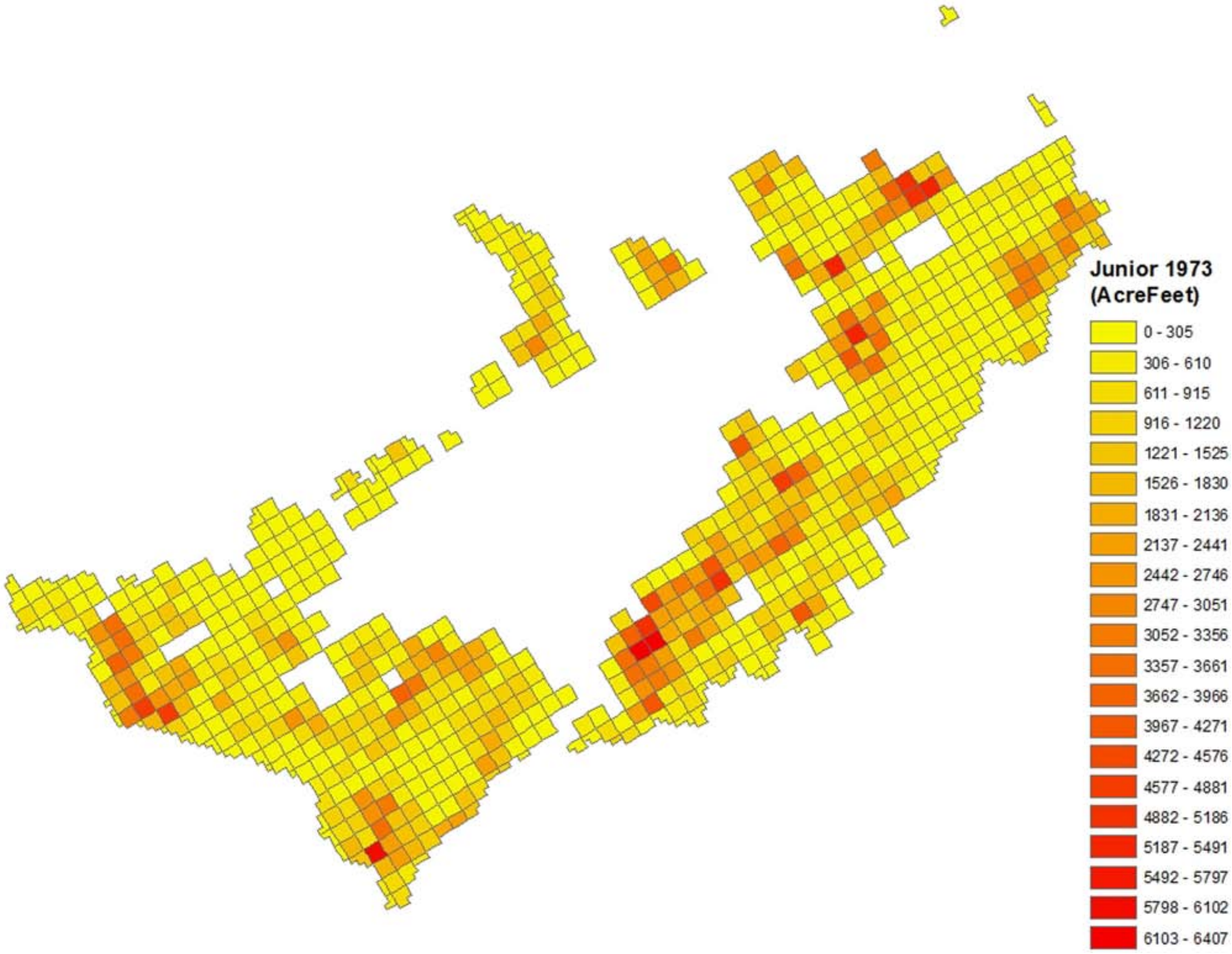

Figure 3. Spatial distribution of the amount of water rights junior to 1973.

function of corresponding per acre applied water w; similarly x is planted acreage; $C_{z,c}$ is costs associated with 1 acre of crop c in zone z excluding irrigation related expenses; $CW_{z,i}$ is per acre-foot cost of irrigation water in zone z under irrigation technology i. The choice variables are $x_{z,c,s,i,ws,\tau}$ and $w_{z,c,s,i,ws,\tau}$.

[20] Per acre crop production functions (yields) are specified according to *Martin et al.* [1989] as a function of applied irrigation water w:

$$Y_{z,c,s,i,\tau} = Ym_{c,s} - (Ym_{c,s} - Yd_{c,s})\left(1 - \frac{w_{z,c,s,i,\tau}}{wm_{c,s,i}}\right)^{\frac{wm_{c,s,i}}{ETm_c - ETd_{c,s}}} \quad (5)$$

[21] Where, Ym is crop yield at maximum irrigation, Yd is nonirrigated yield (dry yield), wm is irrigation depth at full irrigation, ETm is evapotranspiration at Ym, and ETd is evapotranspiration at Yd.

[22] The constraint on availability of various classes of land in each zone is

$$\sum_c x_{z,c,s,i,ws,\tau} \leq LAND_{z,s,i,ws} \ \forall z, s, ws, i, \tau \quad (6)$$

where $LAND_{z,s,i,ws}$ is the acreage of soil type s in zone z that is under irrigation technology i and uses water from water source ws.

[23] Crop mix constraints (equations (7) and (8)) are used to implicitly reflect crop rotation patterns and production resource constraints including capital, agronomic restrictions, labor, etc., by county consistent with previous literature [*Adams et al.*, 2003; *McCarl*, 1982; *Schneider et al.*, 2007].

$$\sum_{(z'\in cnt),s,i,ws} x_{(z'\in cnt),c,s,i,ws,\tau} \leq \sum_h \delta_{cnt,\tau,h} cmix_{c,h,cnt} \cdot \sum_{(z'\in cnt),s,i,ws} LAND_{(z'\in cnt),s,i,ws} \quad \forall c, \tau, cnt \quad (7)$$

$$\sum_h \delta_{cnt,\tau,h} = 1 \quad \forall \tau, cnt \quad (8)$$

Constraints (7) and (8) rely on past h years of planted crop mix acreages to reflect historically observed crop mix patterns in simulated planting decisions over time. Here $cmix_{c,h,cnt}$ is the historical percentage of planted acreage in year h devoted to crop c in a given county (cnt); $\delta_{cnt,\tau,h}$ is a choice variable, between 0 and 1, which shows the percentage of acreage in a given county in simulated year τ that is planted consistent with crop acreage distribution observed in year h. In other words, $\delta_{cnt,\tau,h}$ for a given county (cnt)

and given simulation year (τ) indicates the percentage of total acreage that is planted in that year (τ) in similar crop acreage proportions to historical year h. Clearly, $\delta_{cnt,\tau,h}$, for each county and simulation year have to be less than or equal to 1, and summation of $\delta_{cnt,\tau,h}$ over h in any year (τ) and county (*cnt*) has to be less than or equal to 1 to eliminate the possibility of having more than 100% of acreage allocated to various crops in a given year. Equation (7) constrains planted crop area, x, to be less than or equal to some proportion of the historical crop mix and land availability. Equation (8) determines the specific proportion. These constraints together restrict planted acreage of each crop over the model's multiyear timeframe to be no greater than the maximum that has been observed historically and no less than the minimum that has been observed historically. Additionally, these constraints allow for flexibility in planted crop acreages for each crop as convex combinations of historically planted acreages. This representation allows for some flexibility in planted acreages within the bounds of observed crop mixes in recent years. The convex combination of historical acreages guarantees that simulated planted acreages will reflect crop rotation and other farm level requirements that affect acreage decisions. Notice that equations (7) and (8) are defined over counties (*cnt*) rather than irrigation zones solely because of data limitations. The empirical model groups irrigation zones by county on the basis of their geographic location. Irrigation zones that straddle county borders are assigned to the county that contains the greatest proportion of the zone.

4.2. Incorporating Hydrology Into the Economic Model

[24] Equations (4)–(8) compose the economic optimization model but do not reflect constraints on irrigation water or hydrologic dependencies between irrigation zones and the target area. A number of studies examine aquifer management using combined hydrologic-economic frameworks [*Chen et al.*, 2006; *McCarl et al.*, 1999; *Keplinger et al.*, 1998; *Schiable et al.*, 1999; *Watkins and McKinney*, 1999]. We use hydrologic response functions to quantify the linkages between zones and the target area at Thousand Springs. A similar approach utilizing a formulation based on the response of aquifer head and streamflow to stresses at various locations has previously been used [*Ejaz and Peralta*, 1995]. Hydrologic dependencies have been quantified between different locations within the Snake River Plain aquifer and reaches of the Snake River using groundwater flow response functions [*Cosgrove and Johnson*, 2004, 2005]. Response functions can be useful criteria for subdividing the aquifer into zones for conjunctive management of groundwater and surface water. The actual subdivision of the aquifer by irrigation zones, however, is based on a desired balance between scientific precision and administrative convenience. The temporal distribution of depletion of the Snake River Plain aquifer resulting from pumping across geographically distributed pumping locations has also been quantified [*Cosgrove and Johnson*, 2004, 2005]. The propagation of depletion may be distributed over periods ranging from days to decades depending on the proximity of the pumping location to the surface water body of interest, and the hydraulic properties of the aquifer and streams. The spatiotemporal response functions are obtained from *Contor et al.* [2006], who examined the effects of prior appropriations–based curtailment on spatial distribution of pumping reductions on the basis of seniority of water rights in the ESRPA.

4.3. Policy Scenarios

[25] This model (equations (4)–(10)) was run under three scenarios. In the first scenario, applied groundwater and surface water are constrained to be less than or equal to application levels observed in year 2006. This scenario is included in the analysis to ascertain if the model reproduces observed, "business as usual" crop production patterns. In the second scenario (PA), groundwater user per zone is constrained according to administrative curtailment which shuts off irrigation water rights junior to 1973 (equation (9)). The total amount of pumping in each zone is therefore constrained to be less than or equal to the total amount of water rights with priority dates earlier than 1973 ($\tilde{W}$). The third scenario (PAR) is designed to produce the optimal distribution of pumping reductions per zone subject to a constraint that the pumping reductions under PAR deliver relief at the target location no less than what would be delivered under administrative curtailment over time (equation (10)). In any given year the quantity of water delivered to the Thousand Springs area is measured as the summation of relief generated from curtailment of pumping across all the zones in previous years.

$$\sum_{c,s,i,ws} w_{z,c,s,i,ws,t} \cdot x_{z,c,s,i,ws,t} \leq \tilde{W}_{z,t} \qquad \forall z, t, ws = \text{ground water} \tag{9}$$

$$\begin{aligned} &\sum_{\tau=0}^{t} \sum_{z} \left(\bar{w}_z - \sum_{c,s,i,ws} w_{z,\tau} \cdot x_{z,c,s,i,ws,\tau} \cdot ie_i \right) \Psi_{t-\tau} \\ &\quad \geq \sum_{\tau=0}^{t} \sum_{z} (\bar{w}_z - \tilde{W}_z) \Psi_{t-\tau} \quad \forall t, ws = \text{ground water} \end{aligned} \tag{10}$$

where $\bar{w}_z$ is the amount of consumptively used water under no water shortage and no curtailment per zone, $\tilde{W}_z$ represents water rights senior to 1973, ie_i is irrigation efficiency, $\Psi_{t-\tau}$ is a hydrologic response function measuring the amount of additional water that becomes available at the target area in year t from reducing consumptive use of groundwater by 1 ac ft in zone z in period τ.

[26] We intentionally restrict relief produced by PAR to be no less than relief produced by PA even after administrative curtailment has been lifted. This differs from the current rationale used by IDWR when evaluating alternative mitigation plans. IDWR requires alternative mitigation plans to provide matching relief at the point of interest only for the duration of administrative curtailment. We impose the restriction in equation (10) for 100 years for the sake of exposition and consistency between the two mechanisms (PA and PAR) regardless of the duration of administrative curtailment. Imposing constraint 10 only for the duration of the administrative curtailment would ignore the relief that is generated in the PA scenario in later years. Imposing this constraint only during the period of Administrative Curtailment would relax the restrictions on the PAR scenario resulting in fewer reductions in pumping and less

economic cost under the PAR scenario, further reinforcing our findings.

5. Data

[27] Three categories of data are needed to empirically solve the model. The first category contains crop prices and production costs by crop and zone, as well as irrigation costs in various regions of ESRP (University of Idaho Extension Service, Costs and returns estimates (enterprise budgets), http://www.cals.uidaho.edu/aers/r_crops.htm, accessed 15 February 2011). Area specific data for nine crops (wheat, corn grain, corn silage, barley, sugar beets, dry beans, alfalfa, potatoes, and pasture) are used to parameterize equation (4). We also use county-level crop mixes for the past 10 years (USDA, National Agricultural Statistics Service, data and statistics, http://www.nass.usda.gov/Data_and_Statistics/Quick_Stats_1.0/index.asp, accessed 17 November 2010) in equations (7) and (8).

[28] The second category of data includes crop, soil, and climate characteristics needed to populate crop production functions (equation (5)). Data are obtained from Soil Data Mart (NRCS, 2010), the AgriMet weather database (U.S. Bureau of Reclamation, http://www.usbr.gov/pn/agrimet/, accessed January 2010), University of Idaho Extension publications [*Allen and Robison*, 2007], as well as personal communications with extension agents. Data specifically include growing season precipitation, maximum available precipitation stored in root zone at planting, root zone depth, seasonal *ETm* (full-irrigation evapotranspiration), maximum yields of fully irrigated crops, and irrigation efficiency. Dry (nonirrigated) yield was calculated as a function of *ETm*, *ETd* (evapotranspiration under dryland conditions), and *Ym* (crop yield under full irrigation) [*Doorenbos and Kassam*, 1979; *Allen et al.*, 1998; *Martin et al.*, 1989]. *ETd* was calculated as a function of precipitation stored in root zone at planting and growing season precipitation [*Doorenbos and Kassam*, 1979; *Ponce*, 1989]. Irrigation depths required for maximum yields were calculated as functions of *ETm* and the consumptive use fraction of applied irrigation water (one of many definitions of irrigation efficiency) [*Doorenbos and Kassam*, 1979; *Martin et al.*, 1989]. Equation (6) uses spatially referenced data on soil type acreage, obtained from Soil Data Mart (NRCS, 2010), and spatially referenced data on irrigation technology and water source, obtained from ESPAM 1.1 [*Cosgrove et al.*, 2006].

[29] The third category of data includes hydrologic response functions (equation (10)) as well as the status quo amount of groundwater pumped (equation (9)). These data are obtained from ESPAM 1.1 [*Cosgrove et al.*, 2006] as well as the Eastern Snake Plain Aquifer Model Version 2 (ESPAM2). On the basis of the data in ESPAM 1.1, each zone is assigned a hydrologic response function (relative to the Thousands Springs area); consumptive use of ground and surface irrigation water (based on consumptive use in 2006); water right distribution pre- and post-1973; and the proportion of land irrigated with surface and groundwater sources. Hydrologic response functions for each zone predict the impact of a 1 ac ft groundwater stress per zone on surface water discharge in Thousand Springs over time [*Cosgrove and Johnson*, 2004].

6. Results

[30] The model is first used to simulate a representative production pattern without imposing curtailment restrictions on water use. Water used in each zone is constrained, however, to be no greater than observed use during years with no water calls or curtailment orders. This simulation is intended to provide insight on the accuracy of the model's output. In this simulation water use in each zone is constrained to 2006 levels of consumptive use (obtained from ESPAM 1.1) and simulated crop planted acreage is a convex combination of historical crop mix from 1999 to 2008. The simulated acreage numbers fall between the minimum and the maximum proportions observed over the last 10 years of crop production and provide a reasonable representation of the business as usual scenario. For example, historically between 34% and 42% of planted acreage in Bannock County has been allocated to wheat annually. The model simulates 39% of acreage to be devoted to wheat in Bannock County. Similar results hold for the rest of the crops in the rest of the counties.

[31] The model is used to analyze three scenarios with 1 year, 10 year, and 100 year administrative PA-based curtailment specifications. Different curtailment periods are analyzed because it is difficult to predict how long water users will be curtailed in any given instance. Under the 1 year curtailment specification, administrative curtailment of water rights junior to 1973 is enforced for only 1 year, after which water use is allowed to revert to the business as usual. Under the 10 year curtailment period, administrative curtailment of water rights junior to 1973 is enforced for 10 years. Similarly, the 100 year curtailment scenario corresponds to administrative curtailment of water rights junior to 1973 imposed for 100 years. For each of these three curtailment scenarios the spatial distribution and quantity of pumping is compared between two alternative water management scenarios, PA and PAR. In all three scenarios, PAR is constrained to generate relief at Thousand Springs that is no less than that generated by PA at any point in time, including all future periods beyond the cessation of PA administration. Discount rate of 5% is used for the analysis.

[32] The difference in total pumping in each irrigation zone, $\Delta W_{z,t}$, between prior appropriations doctrine based curtailment with no water reallocation (PA) and curtailment supplemented with optimized water reallocation (PAR) is used to demonstrate the differences in the spatial distribution of pumping over time under the two water management strategies.

$$\Delta W_{z,t} = W_{z,t}^{PAR} - W_{z,t}^{PA} \tag{11}$$

where, $W_{z,t}^{PAR}$ is the amount of water pumped in zone z in year t under curtailment supplemented with optimized water reallocation, and $W_{z,t}^{PA}$ is the amount of water pumped in zone z and year t under strictly prior appropriations–based administrative curtailment with no water reallocation. Obtained values of $\Delta W_{z,t}$ are used to generate Figures 4, 5, and 6. Green shades represent negative values of $\Delta W_{z,t}$ for zones where pumping under a PA is greater than pumping under PAR. Orange shades represent positive values of $\Delta W_{z,t}$, indicating that pumping under the PA scenario is less than under the PAR scenario.

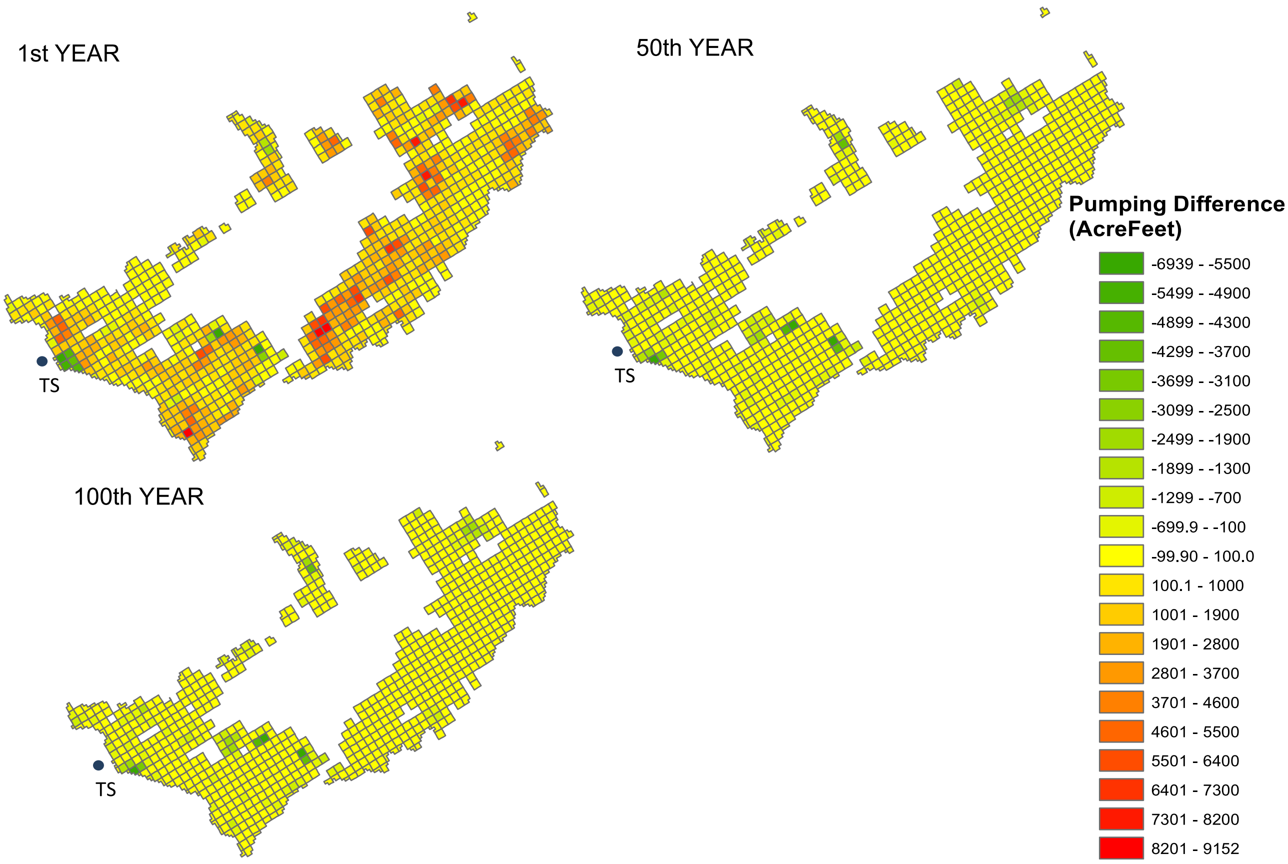

Figure 4. Pumping difference (volume pumped under the PAR scenario minus volume pumped under the prior appropriations (PA) scenario) under 1 year of curtailment, with $r = 0.05$. Green shading indicates areas in which pumping decreased under the PAR scenario compared to pumping under PA scenario. Red shading indicates areas in which pumping increased under the PAR scenario.

[33] Figure 4 shows differences in pumping volumes between the two scenarios in years 1, 50, and 100 assuming administrative curtailment is enforced only for 1 year (specifically the first year of the model). The difference in pumping is greatest in the first year. Since administrative curtailment is only enforced in the first year, pumping levels in the following years revert to the business as usual scenario. Under the PAR scenario, however, pumping continues to be lower in a small number of zones, compared to pumping under administrative curtailment. The reason for this pattern is that equation (10) imposes a requirement that even in years when administrative curtailment is no longer implemented, spring flow in the Thousand Springs area under PAR scenario has to be no less than what would occur under PA scenario. Since PAR achieves optimality by generally moving reductions nearest the target, its relief expires more rapidly than PA relief. Under the constraint adopted here, future reductions must be maintained to sustain the long-delayed relief that would have resulted from distant curtailment under PA.

[34] Pumping differences in years 1, 10, and 100 under 10 years of administrative curtailment are reported in Figure 5. Similar to Figure 4, during the years when administrative curtailment is implemented, there is a change in the spatial distribution and relative pumping levels as a consequence of changing from strict administrative curtailment to one supplemented with optimized water reallocation. When administrative curtailment is no longer being implemented zones revert to a pumping level corresponding to the business as usual outcome. In Figure 6, administrative curtailment is enforced for 100 years. Therefore, in all years there are significant differences between pumping under PAR scenario relative to PA scenario.

[35] In general, the zones which decrease pumping under a PAR scenario relative to a PA scenario tend to be located closer to Thousand Springs. On the other hand, zones which increase pumping under PAR scenario relative to PA scenario tend to be located further away from the Thousand Springs area. This outcome is driven by the fact that, absent any transaction costs, it is generally more efficient for zones further from Thousand Springs to negotiate with users closer to Thousand Springs and pay them to reduce their pumping because the latter users' reduction in pumping is generally more effective in terms of generating additional relief at the Thousand Springs target area. Distant zones generally generate a higher fraction of relief to non-target river and spring reaches.

[36] The appearance of isolated green islands within orange/red regions is caused by the parcel-to-parcel optimization on the basis of crop mix and soil types. Crop mix convexity constraints do not allow the model to reduce acreages of crops below what has been observed during the

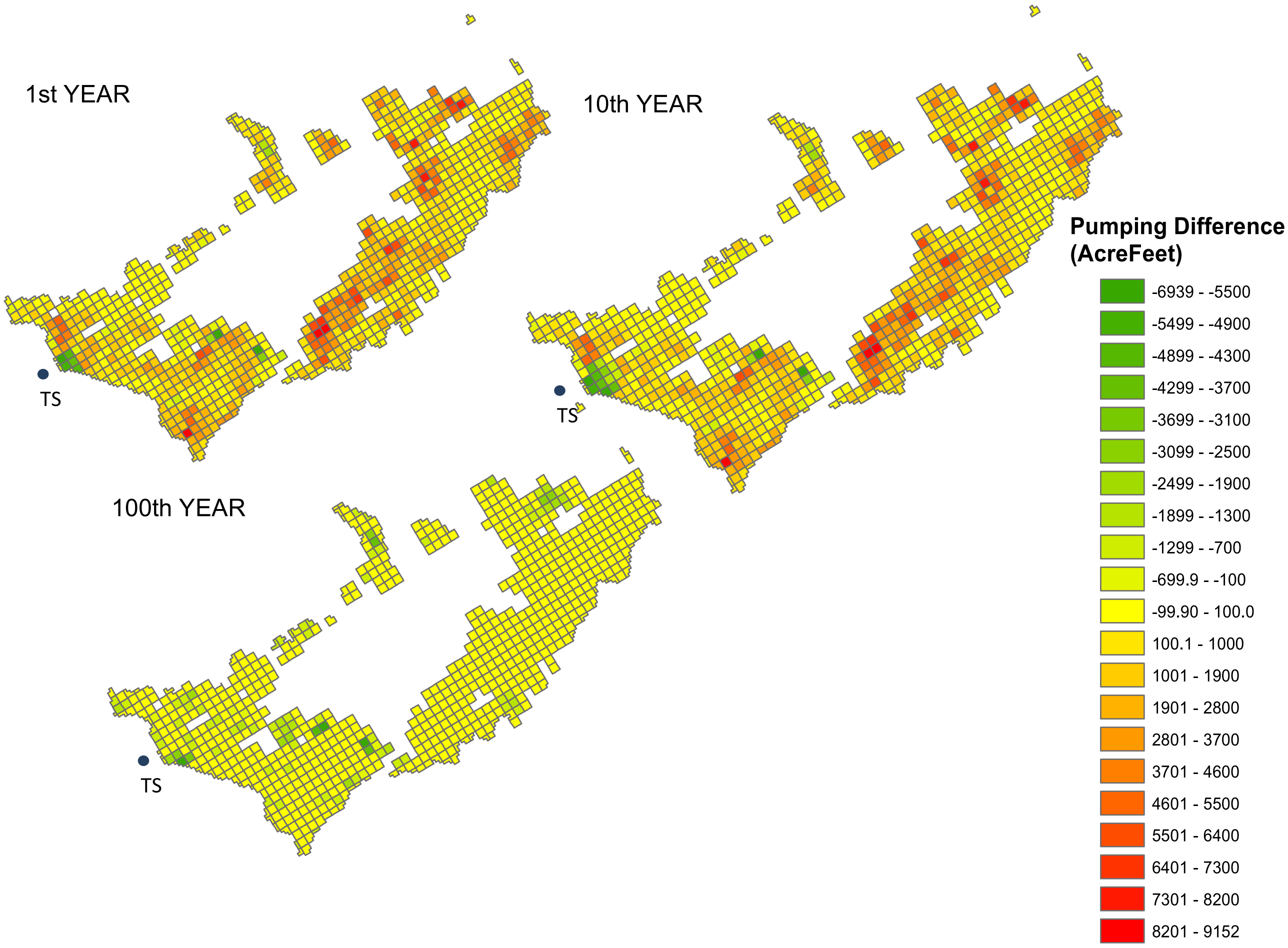

Figure 5. Pumping difference (volume pumped under the PAR scenario minus volume pumped under the PA scenario) under 10 year curtailment, with $r = 0.05$.

past 10 years. Therefore, what could not be achieved via reduction of acreages close to Thousand Springs, because of acreage constraints, has to be generated by foregone pumping in more distant zones. Furthermore, zones with less productive soils, or soils suitable only for lower-valued crops, could rationally be considered for an increase in foregone pumping even though distant from the springs.

[37] Figures 4–6 also reflect local hydrology near the Snake River. The concentration of green zones in the southwest appears in Figures 4–6. This of course represents irrigated lands nearest Thousand Springs for which the delivery call was made. However there is a concentration of darker orange zones not too distant from this area, to the north and to the west. The local hydrology explaining this phenomenon is that those zones are near a very productive spring complex known as the Malad Gorge. Most of the relief from forgone pumping in these zones would be expressed at the Malad Gorge springs and not at the Thousand Springs target area where senior users made the call for water. The optimization model estimates that the costs of curtailment to water users in this area exceed the costs of curtailment in other areas that would generate equivalent benefits at Thousand Springs. Therefore, the model chooses to limit pumping in other zones that have a greater impact (provide greater benefit) on the target area per acre-foot of reduced consumptive use.

[38] Table 1 shows the effects on total pumping from the aquifer over the next 100 years. For a 1 year curtailment, the PAR scenario produces a 0.3% increase in the total amount of pumped water over the next 100 years relative to a PA scenario. Similarly, pumping increases by 3% and 40% for 10 year and 100 year administrative curtailment scenarios, respectively, if optimized water reallocation is allowed. Optimization allows the water call at Thousand Springs to be met with a smaller reduction of pumping under PAR than under PA. As a result, discounted returns to groundwater irrigation are higher under PAR than under PA.

[39] Table 1 also shows ratios of total discounted returns to variable costs of production over the 100 years under PA versus PAR for each curtailment length scenario. At a 5% discount rate, for a 1 year administrative curtailment, optimized reallocation of water use can increase discounted returns over 100 years by 0.3%, not accounting for any potential transaction costs associated with reallocation process. For a 10 year curtailment scenario, discounted returns increase by 2.5%. Similarly, for a 100 year curtailment scenario, discounted returns increase by close to 7%. A 40%

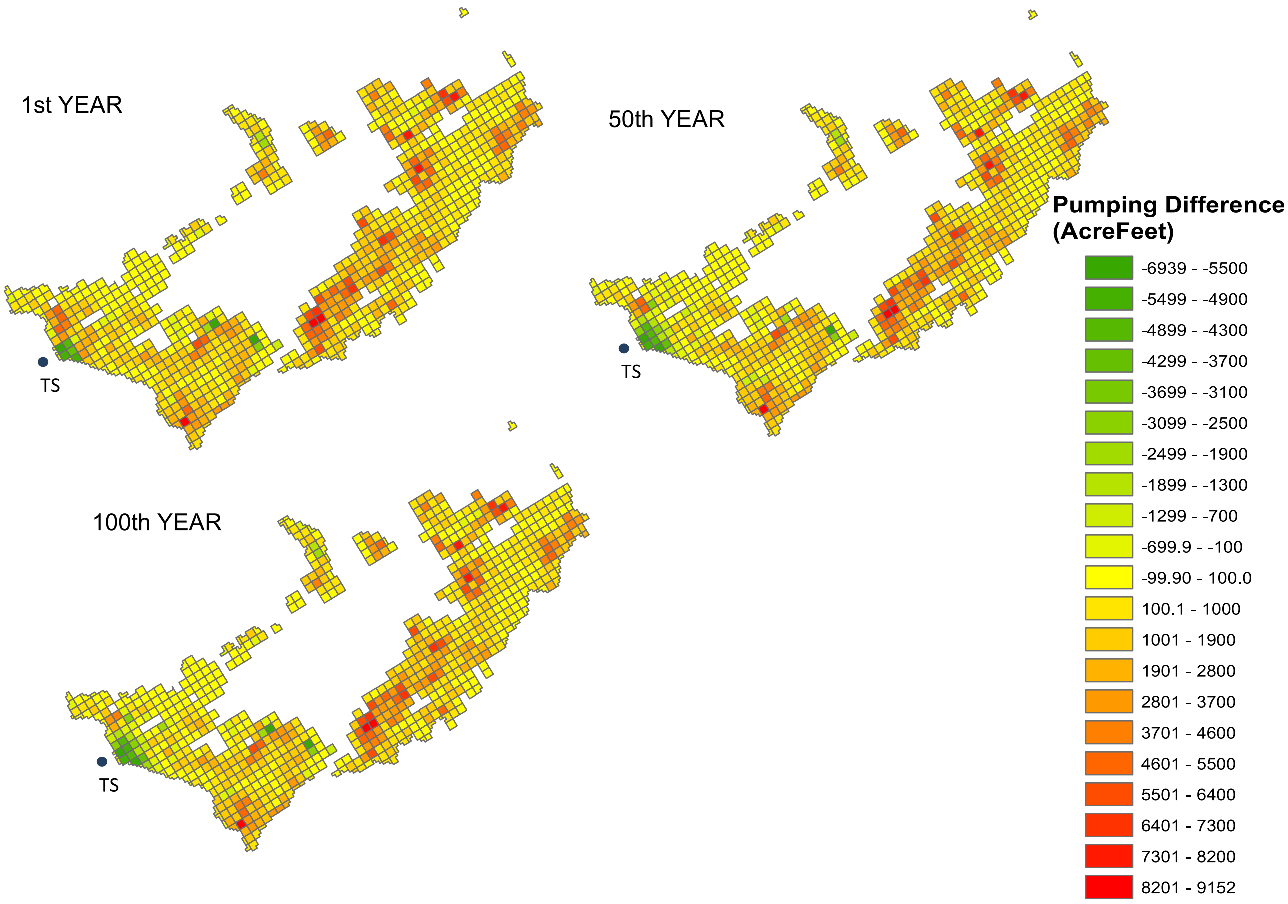

Figure 6. Pumping difference (volume pumped under the PAR scenario minus volume pumped under the PA scenario) under 100 year curtailment, with $r = 0.05$.

increase in pumping produces only 7% increase in discounted net present value of profits over a hundred year period in part because of the decreasing marginal physical product of irrigation water as reflected in production functions used in this model [*Martin et al.*, 1989]. This also results in part because only the financial returns (but not pumping reductions) are discounted, and in part because the crop mix constraint that sustains production of low-value crops necessarily limits production of high-value crops.

Table 1. Comparison of Discounted Returns to Variable Costs of Agricultural Production (Over a 100 year Timeframe) and Total Water Pumped Under PAR and PA Scenarios[a]

	Ratio of Discounted Returns Under PAR Versus PA Scenarios (%)	Ratio of Total Amount of Extracted Water Under PAR Versus PA Scenarios (%)
$r = 0.05$		
1 year	100.31	100.30
10 years	102.56	102.98
100 years	106.85	140.36
$r = 0.07$		
1 year	100.42	100.26
10 years	103.27	102.99
100 years	106.86	140.27

[a]PAR, prior appropriations with reallocations of water use; PA, prior appropriations.

7. Conclusions

[40] The prior appropriations doctrine provides a framework which can be used to address conflicts over water resources during water shortages. In times of water shortages senior water right holders can place a "call" to obtain water to which they are entitled. With the advent of conjunctive administration of groundwater and surface water rights in Idaho, this holds even in situations where the users placing a call have senior surface water rights for spring discharge which is affected by groundwater pumping of junior irrigators, either nearby or distant. The economic efficiency curtailment of junior pumpers can be potentially enhanced by reallocating water rights between pumpers whose wells are hydraulically connected with the affected spring discharge.

[41] Distribution of water right seniority may, in some cases, coincide with the distribution of soil productivity if most productive soils were settled first and hold more senior water rights. In that case, curtailment without water reallocation inadvertently may achieve some efficiency by curtailing least productive producers first. However, PA-based curtailment does not necessarily and cannot explicitly consider productivity and does not account for hydrologic connectivity between curtailed water users and the target area. Supplementing PA-based administrative curtailment with appropriate policies for water right reallocation could incorporate both soil productivity and

hydrologic connectivity, in determining optimal spatiotemporal distribution of curtailment necessary to meet a senior water users' call.

[42] Generally, an increase in the distance between a regulated well and the spring where relief is needed decreases the proportion of conserved groundwater that actually reaches the target area. In addition to having a greater portion of benefit propagated to nontarget locations, administrative curtailments that take place further away from the target area require a longer period of time to generate relief at the target area. If the objective is strictly to deliver to senior water users the amount of additional relief to which they are entitled to under PA doctrine, then, in general, the most efficient means to achieve this objective is to curtail groundwater use hydraulically nearest to the target area.

[43] The empirical results in our model show a different spatiotemporal distribution of reduced pumping under prior appropriations–based curtailment (PA) with no water reallocation versus prior appropriations–based curtailment supplemented with potential water reallocation (PAR), to achieve equivalent relief at the target area. Results also show the overall amount of pumped water from the aquifer over the hundred year horizon to be greater under PAR scenario than under strictly PA scenario. Under PAR, pumping reductions take place closer to the Thousand Springs area, providing greater relief at the Thousand Springs area per acre-foot of reduced pumping. Therefore, it is not surprising that under PAR, pumping reduction that produces the required relief at Thousand Springs, is less than under PA. While the distribution of pumping reductions in the PAR scenario are more economically efficient for fulfilling senior water users' water call in terms of overall profit maximization, they may not be effective at stabilizing aquifer water levels in the long run. The question of aquifer level stabilization deserves a separate investigation and requires different hydrologic specifications; aquifer stabilization is a different goal from providing relief to a specific senior water user. Further, it is not clear whether administrative curtailment may legally be invoked in Idaho to pursue the goal of aquifer stabilization. Different goals of course imply different objective functions and therefore we would expect to see different outcomes. We leave this exercise for future analysis and instead focus on identifying the economically efficient means of fulfilling senior water users' water call during a water shortage.

[44] Conjunctive administration of surface and groundwater resources is complicated because individual groundwater user's activities impact potentially all other surface and groundwater users in the basin to various degrees. Understanding the cause and effect relationships between groundwater pumping (or recharge) and depletion (or accretion) of rivers, springs, and lakes in various locations is essential for making effective and comprehensive water management decisions. In our model we have constrained PAR to never increase pumping in any zone beyond the amount equal to currently existing water rights; hence, PAR like PA will always be superior to the status quo for all nontarget reaches. Nevertheless quantifying and incorporating benefits to the nontarget reaches would change the objective function and therefore the results. Also, in contexts where several spatially distant senior water users might be issuing water calls, analyses similar to the one presented in this study would require a constraint similar to equation (10) for each reach in which senior appropriators have placed a water call. Multidimensional response functions, similar to the ones used in this study, will have to be utilized to reflect how pumping in each zone affects water users along numerous reaches.

[45] A limitation of the model used in this study is that aquifer levels may change over time, and as a result, response functions theoretically might change as well. However, the response functions used here assume that aquifer conditions over the next 100 years will remain constant enough to satisfy the principle of hydrologic superposition [*Reilly et al.*, 1987]. Hydrologic investigation indicates that this is true; response functions are expected to be robust to the magnitude of changes likely during the simulation period [*Cosgrove and Johnson*, 2004]. Moreover, aquifer levels over the next 100 years are also likely to be influenced by other water uses in addition to agriculture. The hydrologic imprecision arising from the assumption of constant response functions is small relative to economic and policy imprecision arising from uncertainty about future commodity prices, crop production practices, and water right administration.

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